Hunting for four-quark state

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24 Nov, 2016

Outline

- 1. Introduction of four-quark state
- 2. Hunting for diquark
- 3. Hunting for multiplets
- 4. Discussion without conclusion

Four-quark states

Nature 498, 280 (2013)

nature International weekly journal of science

NATURE | NEWS

عربي

Quark quartet opens fresh vista on matter

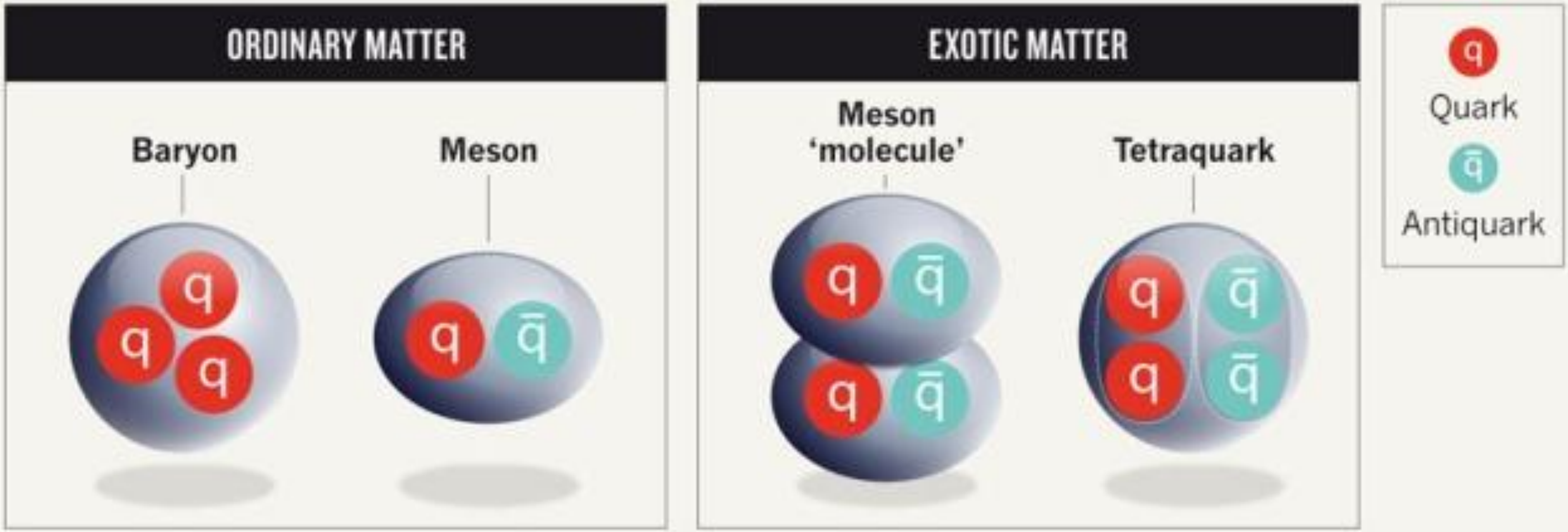
First particle containing four quarks is confirmed.

Devin Powell

18 June 2013

QUARK SOUP

Researchers at colliders in China and Japan have succeeded in making exotic matter comprising four quarks, but are still debating whether the fleeting particles are meson pairs or true tetraquarks.



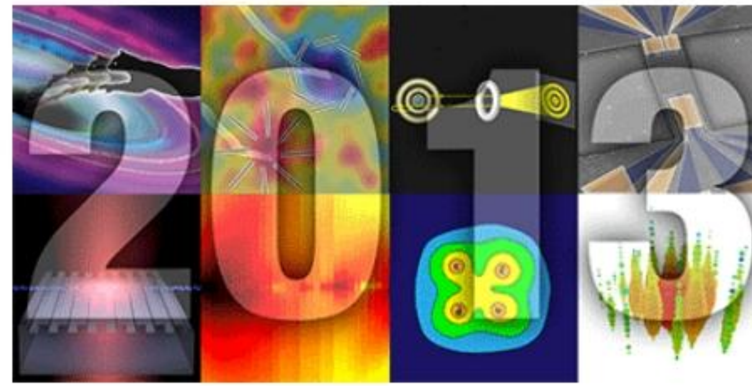
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

Science & Environment

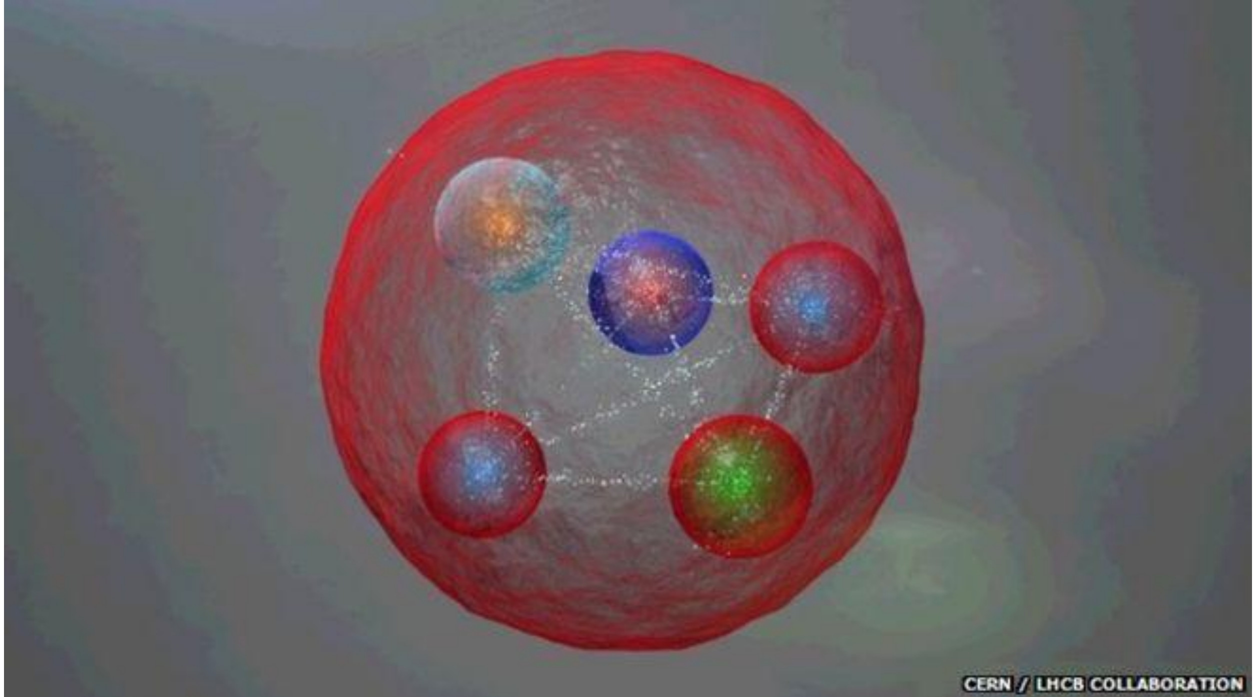
Large Hadron Collider discovers new pentaquark particle

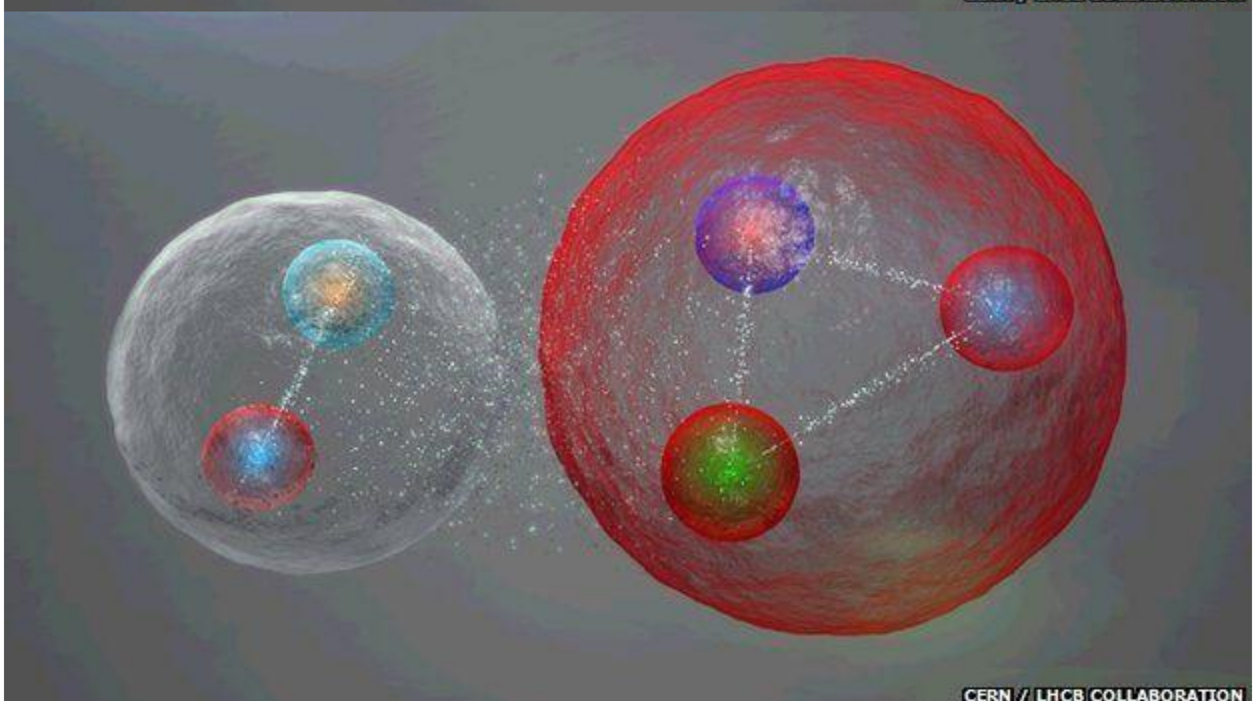
By Paul Rincon
Science editor, BBC News website

14 July 2015 | Science & Environment

UPFRONT 15 July 2015

Pentaquark discovery at LHC shows long-sought new form of matter


CERN / LHCB COLLABORATION


CERN / LHCB COLLABORATION

1. Introduction of four-quark state

Four-quark state was first mentioned by M Gell-Mann

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

Four-quark state was first studied in hadron scattering amplitudes:

“Possibility of baryon - anti-baryon enhancements with unusual quantum numbers”， J.L. Rosner, Phys. Rev. Lett. 21, 950 (1968)

Baryonium:

Hong-Mo Chan and H. Hogaasen, Phys. Lett. B72, 121 (1977)

There have been discovered recently in experiments a number of new states in the $N\bar{N}$ spectrum with masses ranging from below thresholds to about 3 GeV [1]. Some of the states are wide with typical hadronic widths of around 100 MeV, while others are narrow with widths consistent with the experimental resolution of about 10 MeV, even at high masses. Most of these states are characterized by an unexpected reluctance for decaying into meson modes, as inferred either from the measured branching ratios, or from their small total widths. They are therefore popularly called "baryoniums", and are generally regarded as candidates for the long-sought multiquark bound states, probably $qq\bar{q}\bar{q}$.

Mesons in the 10, bar 10 and 27 representations of the flavor SU(3) required!

D P Roy, J. Phys. G. 30, R113 (2004)

Figure 1. The quark duality diagrams for (a) meson–meson, (b) meson–baryon, (c) baryon–antibaryon and (d) baryon–baryonium scatterings. The last one is the formation channel for pentaquarks.

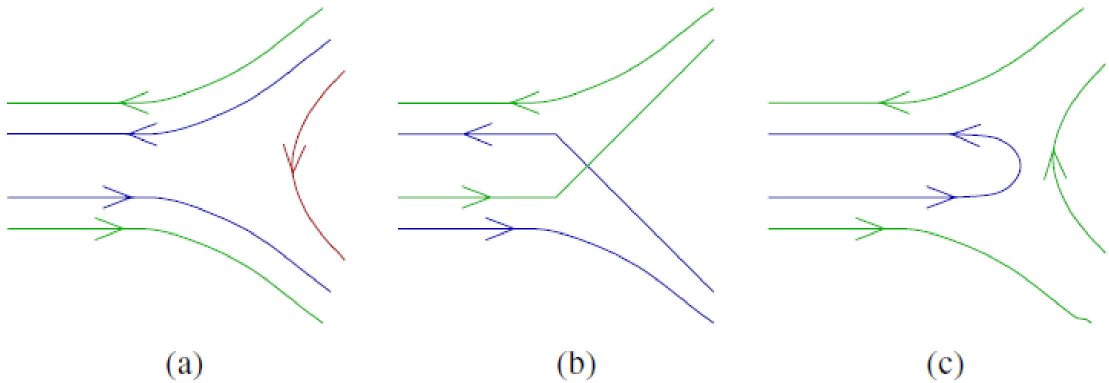


Figure 2. The coupling of baryonium into (a) baryon–antibaryon and (b), (c) meson–meson channels. Only the first one is OZI allowed.

so that enforcing either one of them was enough. In view of the preferential coupling of the $(qq\bar{q}\bar{q})$ mesons to the baryon–antibaryon pair they were later christened as baryoniums in analogy with the heavy quarkonium states [12]. One can easily check that the same rule would

[12] Chew G F 1976 *Proc. Antiproton-Proton Conf. (Stockholm)*

Naive Quark model

The model was proposed independently by Gell-Mann and Zweig, M. Gell-Mann, Phys.Lett.8 (1964): 214; G. Zweig, CERN Report No.8182/TH.401(1964).

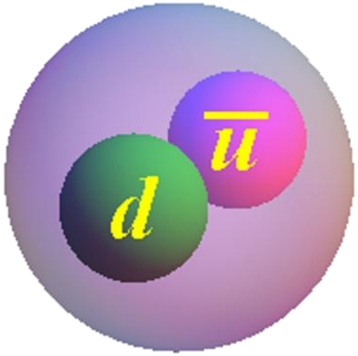
Three fundamental building blocks 1960's (p,n,λ) $\Rightarrow$ 1970's (u,d,s)

Mesons are bound states of a of quark and anti-quark:

Can make up "wave functions" by combing quarks:

$$\pi^+ = u\bar{d},\quad \pi^- = d\bar{u},\quad \pi^o = \frac{1}{\sqrt{2}}(u\bar{u} - d\,\bar{d}),\quad k^+ = d\bar{s},\quad k^o = d\bar{s}$$

$$\pi^- = (d\bar{u})$$



Mesons are in the 1, 8 representations of the flavor SU(3)

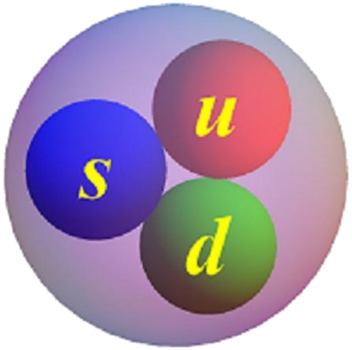
Baryons are bound state of 3 quarks:

proton = (uud), neutron = (udd), Λ= (uds)

anti-baryons are bound states of 3 anti-quarks:

$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

Λ = (uds)



Baryons are in the 1, 8, 10 representations of the flavor SU(3)

Exotic hadrons

Conventional hadrons: Mesons, Baryons

There may exist: Exotic hadrons ("exotica")

g^2, g^3,...

glueballs

qqg, q^3g,...

hybrids

q^2q^2, q^4q,...

multiquarks

Possible quark and anti-quark combinations are of the form:

$$(3q)^p (q\bar{q})^n \quad (p, n \geq 0)$$

For example:

$$qqqqqq \quad p = 2, n = 0$$

$$q\bar{q}q\bar{q} \quad p = 0, n = 2$$

$$qqqq\bar{q} \quad p = 1, n = 1$$

Problem: where will the combinations stop?

Exotic quantum numbers

For a quark-antiquark pair, the following quantum numbers J^{PC} are not allowed:

$$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$$

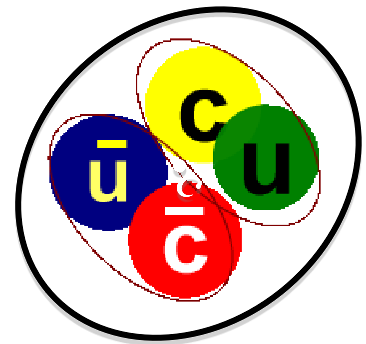
"Exotica"

1, **exotic hadrons such as glueballs, hybrids and multiquark states etc.**
2, **resonances with exotic quantum numbers**

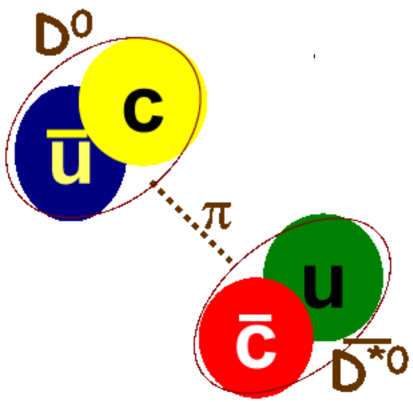
Four-quark states in constituent quark model

Four-quark state: consists of four quarks and anti-quarks

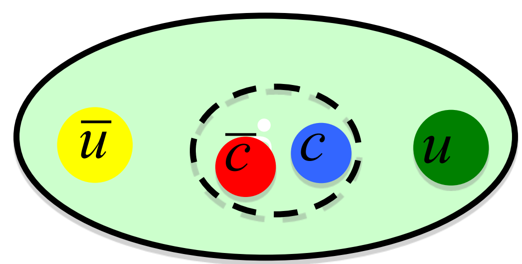
Intrinsic quarks/anti-quarks may make different clusters, and there may be different kinds of four-quark states



(1) Tetraquark



(2) Meson molecule

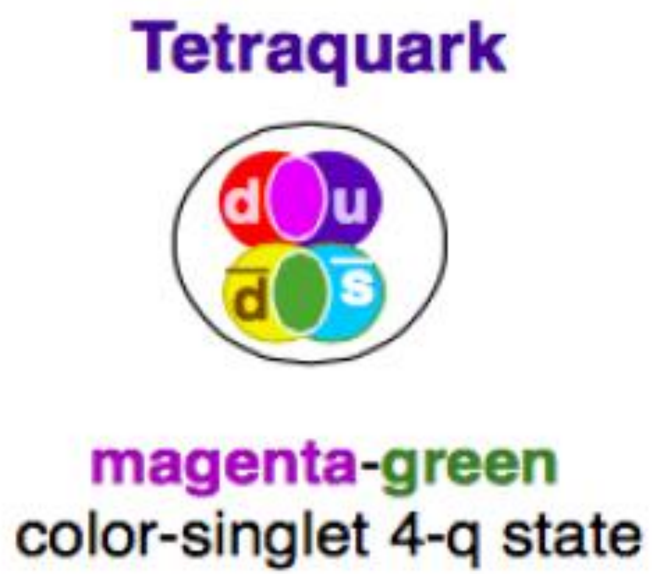


(3) Hadro-charmonium

(4) ??

♢ $(qq)(\bar{q}\bar{q})$ (tetraquark state, baryonium)

Quark dynamics



Diquark-antidiquark with gluon exchange

Spin-independent interaction(Coulombic + linear confinement)

Spin-dependent interaction(color magnetic spin-spin interaction between the quarks(one gluon exchange))

VOLUME 93, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2004

New Look at Scalar Mesons

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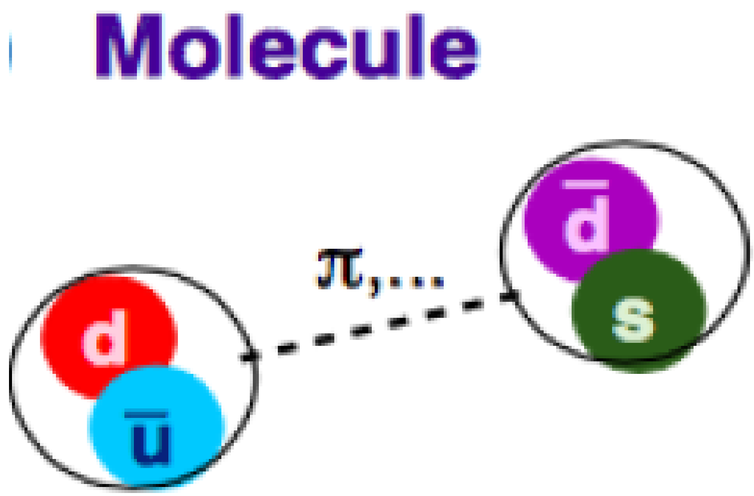
(Received 1 July 2004; published 16 November 2004)

Light scalar mesons are found to fit rather well a diquark-antidiquark description. The resulting nonet obeys mass formulas which respect, to a good extent, the Okubo-Zweig-Iizuka (OZI) rule. OZI allowed strong decays are reasonably reproduced by a single amplitude describing the switch of a $q\bar{q}$ pair, which transforms the state into two colorless pseudoscalar mesons. Predicted heavy states with one or more quarks replaced by charm or beauty are briefly described; they should give rise to narrow states with exotic quantum numbers.

◇ $(q\bar{q})(q\bar{q})$ (molecule)



2 color-neutral mesons with soft pion exchange

$(q\bar{q})$ **is kept together by hadron exchange forces (one-pion exchange, or two-gluon exchange)**

M B Voloshin, and L Okun, "Hadron Molecules and Charmonium Atom", JETP Lett. 23 (1976) 333-336

Presented lattice criteria do not distinguish between tetraquarks and molecules

Hydronic molecules and the charmonium atom

M. B. Voloshin and L. B. Okun'

Institute of Theoretical and Experimental Physics
(February 16, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 6, 369–372 (20 March 1976)

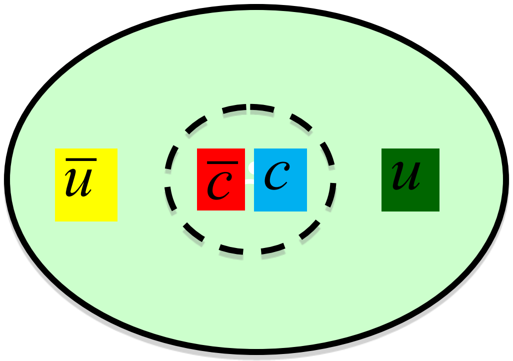
We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons ($\omega, \rho, \epsilon, \phi$, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.

PACS numbers: 12.40.Dd, 14.40.–n

A large aggregate of data indicates that ψ, ψ', and other "psions" (χ, P_C, X) are different states of charmonium, a bound state of c and $\bar{c}$ quarks.[1] One cannot speak as yet, however, of a quantitative agreement between the charmonium model and the experimental data with on the level positions and widths. We wish to note here that it is necessary to superimpose on the simple quark-gluon "atomic" structure of charmonium a much more complicated and in a certain sense fundamental structure of levels of "molecular" type, which represent bound states of a charmed hadron and a charmed antihadron, for example bound and (or) resonant dimension states $D\bar{D}$ ($D^+ = c\bar{n}$, $D^0 = c\bar{p}$) as well as states of the type $C\bar{C}$, where C is a charmed baryon.

◇ Hadro-charmonium

S. Dubynskiy, M.B. Voloshin, Phys.Lett. B666 (2008) 344



A B S T R A C T

We argue that relatively compact charmonium states, J/ψ, $\psi(2S)$, χ_c, can very likely be bound inside light hadronic matter, in particular inside higher resonances made from light quarks and/or gluons. The charmonium state in such binding essentially retains its properties, so that the bound system decays into light mesons and the particular charmonium resonance. Thus such bound states of a new type, which we call hadro-charmonium, may explain the properties of some of the recently observed resonant peaks, in particular of $Y(4.26)$, $Y(4.32\text{–}4.36)$, $Y(4.66)$, and $Z(4.43)$. We discuss further possible implications of the suggested picture for the observed states and existence of other states of hadro-charmonium and hadro-bottomonium.

Argument!

The discussed here hadronic objects, containing a particular charmonium state embedded in a light hadronic matter, can be called hadro-charmonium. We believe that it is appropriate and helpful to distinguish such objects from ‘molecular’ states as well as from more generic multiquark ones. The molecular states, like $X(3872)$, contain pairs of heavy-light mesons that largely do not overlap within the ‘molecule’, while possible more tightly bound states where the heavy and light quarks and antiquarks (quasi)randomly overlap would be generic multiquark states. In hadro-charmonium the heavy and light degrees of freedom are separated by their size scale rather than spatially: a compact colorless charmonium sits inside a larger ‘blob’ of light hadronic matter [11]. The interaction between colorless charmonium ‘kernel’ and the light ‘shell’ is through a QCD analog of the van der Waals force. We argue that for a relatively compact charmonium state the interaction may be sufficiently weak to preserve its particular quantum state, i.e., to prevent a breakup of the charmonium or a strong mixing with other charmonium states. On the other hand, we argue that the same interaction is sufficiently strong to form a bound system, at least in the case where the light hadronic state is that of a highly excited resonance. The observation of the Y

Qian Wang et al., "Y(4260): Hadronic molecule versus hadro-charmonium interpretation", Phys.Rev. D89 (2014),034001

PHYSICAL REVIEW D **89,** 034001 (2014)

$Y(4260)$: Hadronic molecule versus hadro-charmonium interpretation

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(Received 19 December 2013; published 3 February 2014)

In this paper we confront both the hadronic molecule and the hadro-charmonium interpretations of the $Y(4260)$ with the experimental data currently available. We conclude that the data support the $Y(4260)$ being dominantly a $D_1\bar{D}+\text{c.c.}$ hadronic molecule while they challenge the hadro-charmonium interpretation. However, additional data are necessary to allow for stronger conclusions.

Lessons from hydrogen atom

$$V(r) = -\frac{e^2}{4\pi\epsilon_0}\frac{1}{r}$$

Strong interaction among quarks

Physical picture of four-quark states ?

Mixing

Hadrons are in color singlets

1, $(qq)(\bar{q}\bar{q})$ **may mix with** $(q\bar{q})(q\bar{q})$
2, four-quark state may mix with normal $q\bar{q}$ **meson**

Crypto-exotic states

$$|meson> = |q\bar{q}> + |(qq)(\bar{q}\bar{q})> + |(q\bar{q})(q\bar{q})>$$ **+......**

Intrinsic color, flavor configurations could not be distinguished except that special observable is established.
Unfortunately, no such an observable has been definitely set up

Morgan's pole counting rule (D. Morgan, Nucl.Phys.A543,632 (1992))

Four-quark states dynamics

?

Experimental signal?

A. De Rujula, Howard Georgi, S.L. Glashow, Phys.Rev.D12, 147(1975)

the strong and electromagnetic part of the Hamiltonian for a color neutral threequark of quark-antiquark hadron state has the following form:

$$H = L(\vec{r}_1, \vec{r}_2, \ldots) + \sum_i \left(m_i + \frac{\vec{p}_i^{\,2}}{2m_i} + \cdots \right)$$

$$+ \sum_{i>j} (\alpha Q_i Q_j + k\alpha_s) S_{ij} . \qquad (1)$$

In (1), L describes the universal interaction responsible for quark binding; r_i, p_i, m_i, and Q_i are the position, momentum, mass, and charge of the ith quark; and k is $-\frac{4}{3}$ for mesons and $-\frac{2}{3}$ for baryons. The two-body Coulombic interaction is S_{ij}, which has the form

$$S_{ij}=\frac{1}{|\vec{r}|}-\frac{1}{2m_im_j}\left(\frac{\vec{p}_i\cdot\vec{p}_j}{|\vec{r}|}+\frac{\vec{r}\cdot(\vec{r}\cdot\vec{p}_i)\vec{p}_j}{|\vec{r}|^3}\right)-\frac{\pi}{2}\delta^3(\vec{r})\left(\frac{1}{m_i^2}+\frac{1}{m_j^2}+\frac{16\vec{s}_i\cdot\vec{s}_j}{3m_im_j}\right)$$

$$-\frac{1}{2|\vec{r}|^3}\left\{\frac{1}{m_i^2}\vec{r}\times\vec{p}_i\cdot\vec{s}_i-\frac{1}{m_j^2}\vec{r}\times\vec{p}_j\cdot\vec{s}_j+\frac{1}{m_im_j}\left[2\vec{r}\times\vec{p}_i\cdot\vec{s}_j-2\vec{r}\times\vec{p}_j\cdot\vec{s}_i-2\vec{s}_i\cdot\vec{s}_j+6\frac{(\vec{s}_i\cdot\vec{r})(\vec{s}_j\cdot\vec{r})}{|\vec{r}|^2}\right]\right\}+\cdots, \tag{2}$$

where $\vec{r}=\vec{r}_i-\vec{r}_j$ and $\vec{s}_i$ is the spin of the ith quark, and in (1) and (2) $\cdots$ denotes neglected relativistic corrections.

S. Zouzou, B. Silvestre-Brac, C. Gignoux, J.M. Richard, Z.Phys.C30, 457(1986)

Abstract. In the framework of simple non-relativistic potential models, we examine the system consisting of two quarks and two antiquarks with equal or unequal masses. We search for possible bound states below the threshold for the spontaneous dissociation into two mesons. We solve the four body problem by empirical or systematic variational methods and we include explicitly the virtual meson-meson components of the wave function. With standard two-body potentials, there is no proliferation of multiquarks. With unequal quark masses, we obtain however exotic $(\bar{Q}\bar{Q}qq)$ bound states with a baryonic antidiquark-quark-quark structure very analogous to the heavy flavoured $(Q'qq)$ baryons.

Nils A. Törnqvist, Z.Phys.C61,525(1994); Phys.Lett. B590,209 (2004) .

The general one-pion exchange potentials as a function of r

$$V_\pi(r) = -\gamma V_0 [D \cdot C(r) + S_{12}(\hat{r}) \cdot T(r)],$$

where D is as above, $\hat{r}$ is the unit vector, and the r dependence is given by the functions

$$C(r) = \frac{\mu^2}{m_\pi^2} \frac{e^{-\mu r}}{m_\pi r},$$

$$T(r) = C(r) \left[1 + \frac{3}{\mu r} + \frac{3}{(\mu r)^2}\right],$$

and the tensor operator in r space:

$$S_{12}^{NN}(\hat{r}) = [3(\boldsymbol{\sigma}_1 \cdot \hat{r})(\boldsymbol{\sigma}_2 \cdot \hat{r}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2] / \langle \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \rangle_{11},$$

$$S_{12}^{VV}(\hat{r}) = [3(\Sigma_1 \cdot \hat{r})(\Sigma_2 \cdot \hat{r}) - \Sigma_1 \cdot \Sigma_2] / \langle \Sigma_1 \cdot \Sigma_2 \rangle_{11},$$

$$S_{12}^{PV}(\hat{r}) = [3(\varepsilon_1 \cdot \hat{r})(\varepsilon_2^* \cdot \hat{r}) - 1].$$

E.S.Swanson, Phys.Lett. B588,189 (2004) ; Phys.Lett. B598, 197 (2004).

The effective potential from one-pion exchange

$$V_\pi = -\gamma V_0 \left[\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} C(r) + \begin{pmatrix} 0 & -\sqrt{2} \\ -\sqrt{2} & 1 \end{pmatrix} T(r) \right],$$

where

$$C(r) = \frac{\mu^2}{m_\pi^2} \frac{e^{-\mu r}}{m_\pi r},$$

$$T(r) = C(r)\left(1 + \frac{3}{\mu r} + \frac{3}{(\mu r)^2}\right),$$

and

$$V_0 \equiv \frac{m_\pi^3}{24\pi} \frac{g^2}{f_\pi^2} \approx 1.3 \text{ MeV}.$$

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys.Rev.D71, 014028(2005)

Hadron masses from three ingredients: quark composition, constituent quark masses and spin-spin interactions.
The Hamiltonian is

$$H = \sum_i m_i + \sum_{i<j} 2\kappa_{ij}(S_i \cdot S_j)$$

and the sum runs over the hadron constituents. The coefficients κ_{ij} depend on the flavor of the constituents i, j and on the particular color state of the pair.

Applied to the L=0 mesons, K and K^*, gives

$$M = m_q + m_s + \kappa_{s\bar{q}}\left[J(J+1) - \frac{3}{2}\right].$$

Applied to uds states, Λ (good diquark, S=0), Σ and Y^* (bad diquark, S=1), gives

$$M(S,J) = 2m_q + m_s + (\kappa_{qq})_{\bar{3}}\left[S(S+1) - \frac{3}{2}\right] + (\kappa_{qs})_{\bar{3}}\left[J(J+1) - S(S+1) - \frac{3}{4}\right].$$

Four-quark states decay

Decay mode?

Experimental signal?

Four-quark decays

A. De Rujula, Howard Georgi, S.L. Glashow, Phys.Rev.Lett, 38,317(1977)

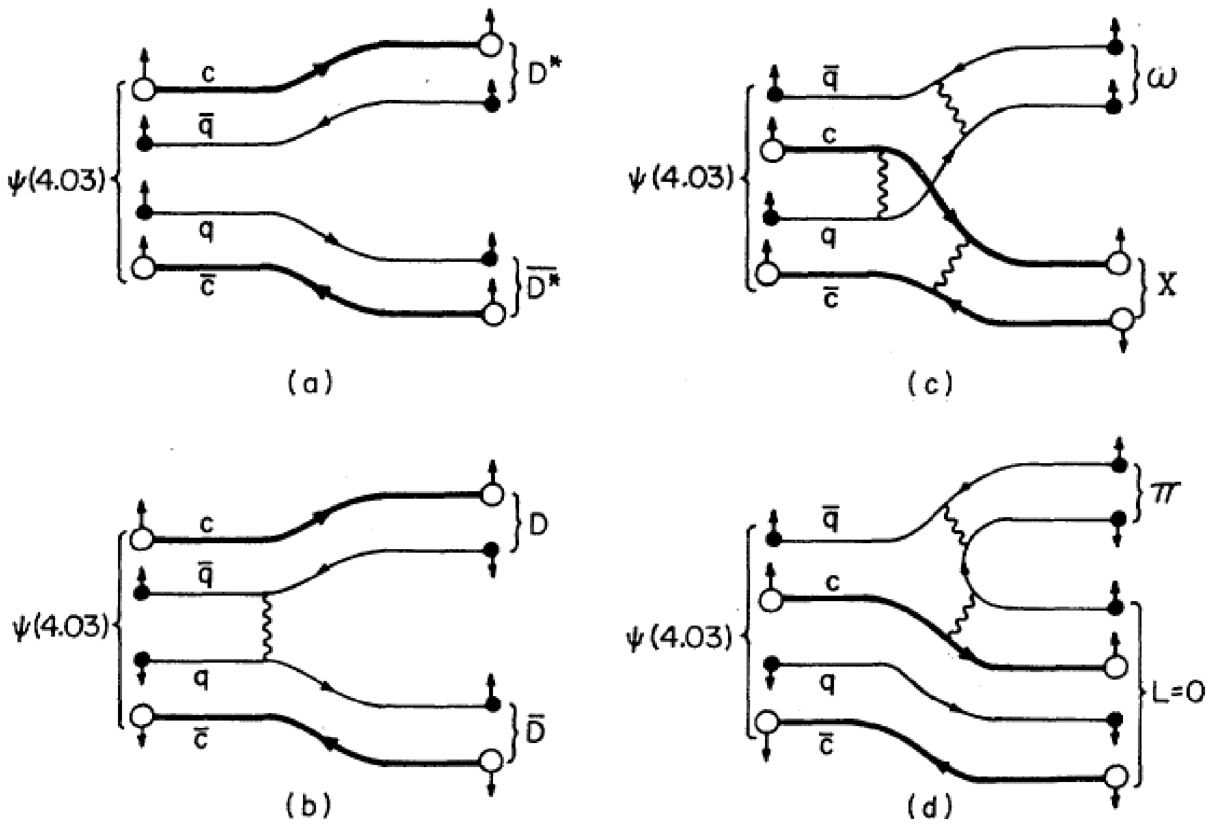
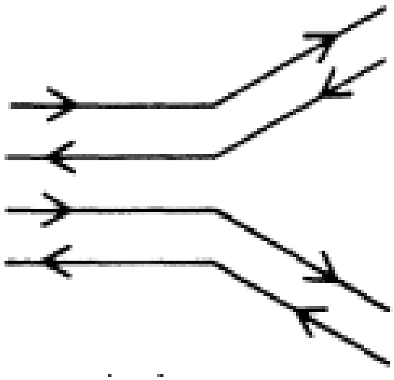


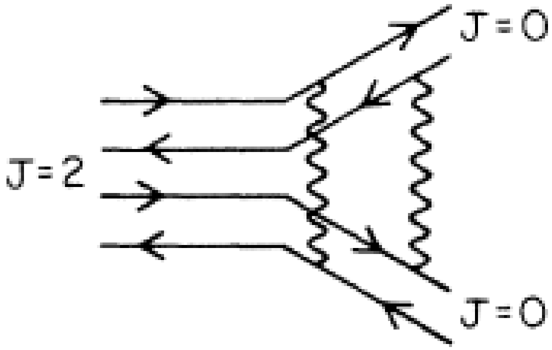
FIG. 1. Some quark diagrams representing decays of molecular charmonium: (a) Simple dissociation, (b) dissociation with spin rearrangement, (c) quark rearrangement, (d) molecular transition.

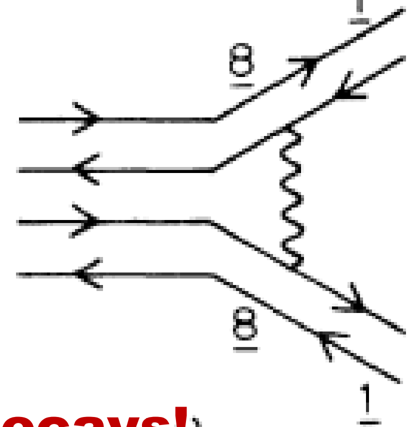
R.J.Jaffe, Phys.Rev.D15, 267(1977); D.V. Bugg, Eur.Phys.J. C47,57 (2006)

OZI super-allowed decay (fall apart):



A given Q'Q' meson cannot "fall apart“ or "dissociate" into any arbitrary QQ mesons.
The decay products must be S-wave mesons in relative S waves.





Suppressed decays!

The OZI-superallowed decays of a $Q^2\overline{Q}^2$ state are calculated by a change of coupling transformation. Any $Q^2\overline{Q}^2$ state may be written as a linear superposition of $(Q\overline{Q})(Q\overline{Q})$ states coupled to the same *total* flavor, spin, and color (singlet). *The recoupling coefficients*, which weight the terms in the sum, *tell us the amplitude for the $Q^2\overline{Q}^2$ meson to dissociate into that particular channel*. Thus,

W. Roberts, B. Silvestre-Brac and C. Gignoux, Phys.Rev.D41, 182(1990)

PHYSICAL REVIEW D VOLUME 41, NUMBER 1 1 JANUARY 1990

Baryon-antibaryon decays of four-quark states

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(Received 20 July 1989)

We classify all the SU(3) multiplets of T-diquonia consistent with the Pauli principle, and estimate their masses using a potential model. Within the framework of the $^3P_0$ model, we calculate the total and partial decay widths of these states into baryon-antibaryon pairs. We find that both the total widths and the partial widths range from a few MeV to several hundred MeV. We briefly discuss implications for experimental detection of diquonia.

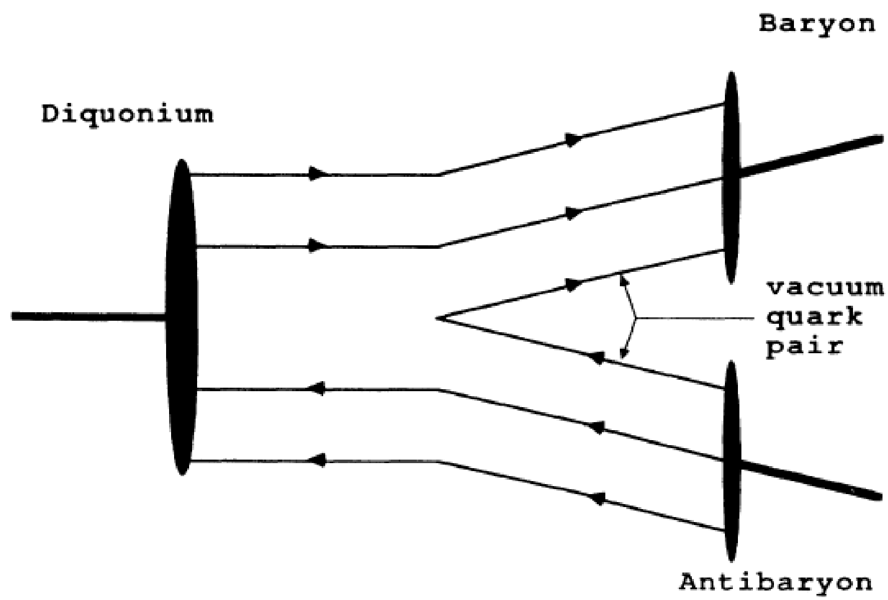


FIG. 2. Diquonium decay into baryon-antibaryon pair via pair creation model.

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys.Rev.Lett, 93,212002(2004)

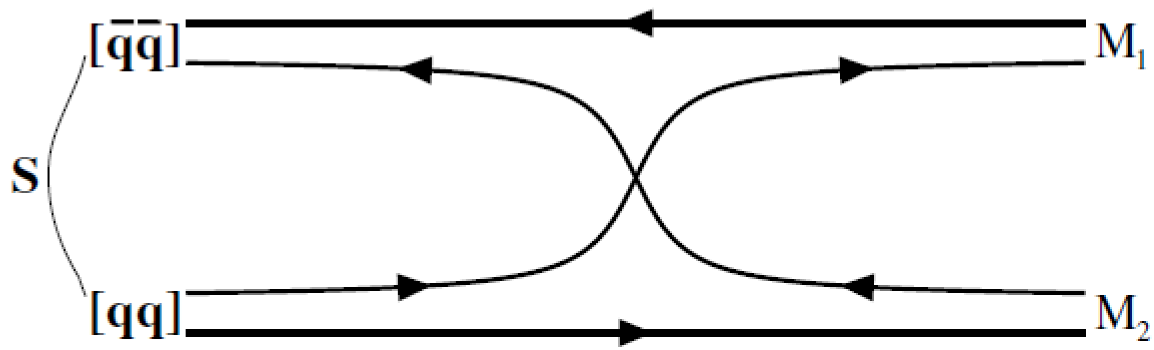
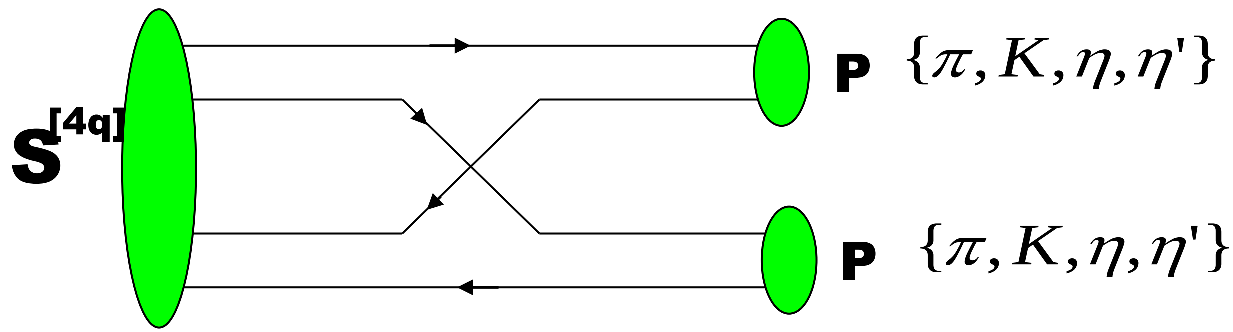


FIG. 1. The decay of a scalar meson S made up of a diquark-antidiquark pair in two mesons M_1M_2 made up of standard $(q\bar{q})$ pairs.

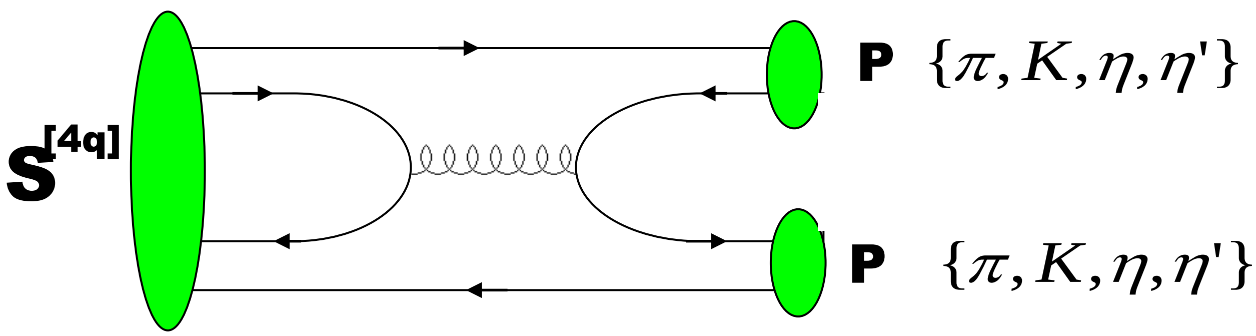
$$\mathcal{L} = A\left[f_0\left(-\frac{\bar{K}K}{\sqrt{2}} + \eta_q\eta_s\right) - \sigma_0\left(\frac{\pi\cdot\pi}{2} + \frac{\eta_q^2}{2}\right) + a^0\left(\frac{\bar{K}\tau_3 K}{\sqrt{2}} - \pi^0\eta_s\right) + \left(\frac{\bar{K}^+\pi^0}{\sqrt{2}} + \bar{K}^0\pi^-\right)\kappa^+ + \ldots\right].$$

F. Giacosa, Phys. Rev. D74,014028(2006);

Dominant (a) and subdominant (b) contributions to the transition amplitudes of a scalar-tetraquark state into two pseudoscalar mesons



Dominant



Subdominant

The Lagrangian for the scalar-pseudoscalar interaction:

$$\mathcal{L} = \langle \tfrac{1}{2}(\partial_\mu \mathcal{P})^2 - \mathcal{P}^2 \chi_P \rangle + \mathcal{L}^P_{\text{mix}} + \langle \tfrac{1}{2}(\partial_\mu \mathcal{S})^2 - \mathcal{S}^2 \chi_S \rangle$$
$$+ \mathcal{L}^S_{\text{mix}} + c_1 \mathcal{S}_{ij} \langle A^i \mathcal{P}^t A^j \mathcal{P} \rangle - c_2 \mathcal{S}_{ij} \langle A^i A^j \mathcal{P}^2 \rangle,$$

Stanley J. Brodsky, Dae Sung Hwang, and Richard F. Lebed, Phys.Rev.Lett, 113,112001(2014)

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\left(\frac{\sigma}{\sqrt{\pi}}\right)^3 e^{-\sigma^2 r^2}\mathbf{S}_c \cdot \mathbf{S}_{\bar{c}},$$

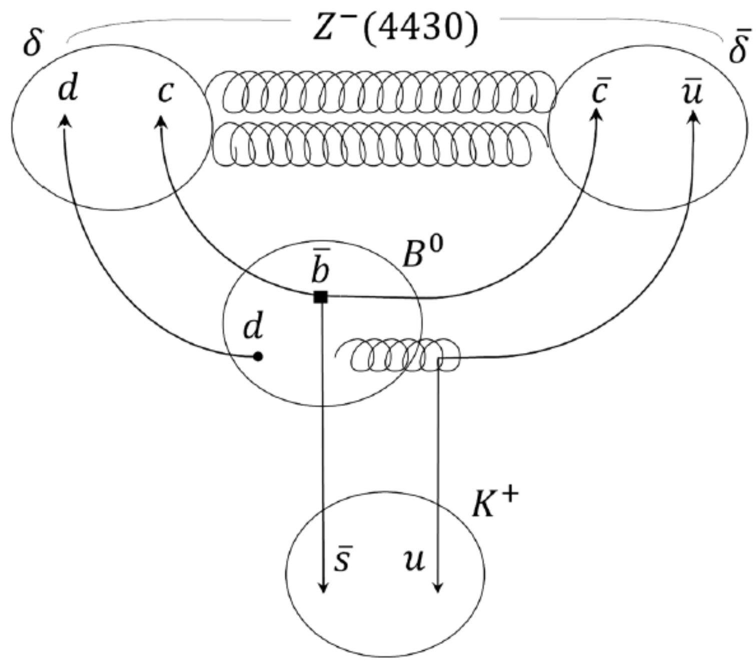


FIG. 2. Illustration of the production of a spatially extended diquark-antidiquark state $\delta\bar{\delta}$ attracted by long-range color forces (indicated by gluon lines). Here, the mechanism is illustrated for $B^0 \to Z(4430)^- K^+$, where the filled square indicates the $\bar{b}$-quark weak decay.

Candidates of four-quark states

Light hadrons

◇ Scalar: $f_0(600)$ (or σ), $f_0(980)$, $a_0(980)$ and the unconfirmed $\kappa(800)$?

◇ X(1860)

Anomalous enhancement near the threshold of $p\overline{p}$ mass spectrum at BES III

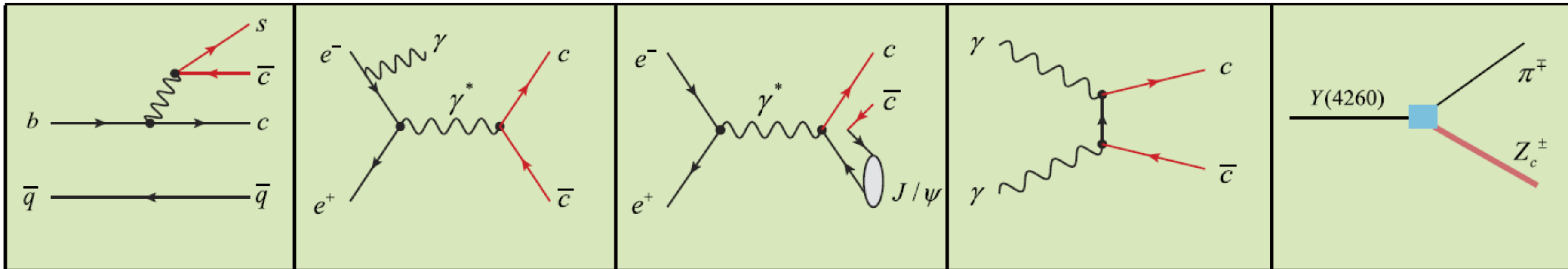
J. Z. Bai, et al., (BES Collaboration), Phys. Rev. Lett. 91, 022001 (2003); Chin.Phys.C34, 421(2010)

The observations at BES

- ★ X(1840): J^P unknown, $J/\psi \to \gamma\, 3(\pi^+ \pi^-)$ **PRD 88, 091502**
- ○ X(1870): J^P unknown, $J/\psi \to \omega\, (\eta\pi\pi)$ PRL107, 182001
- ▲ X(1835): $J^P = 0^-$, $J/\psi \to \gamma\, (\eta'\pi\pi)$ PRL106, 072002
- ■ X($p\bar{p}$): $J^P=0^-$, $J/\psi \to \gamma\, (p\bar{p})$ PRL108,112003
- + X(1810): $J^P=0^+$,J $J/\psi \to \gamma\, (\omega\phi)$ PRD 87, 032008

X(18??) are close to the threshold of proton and anti-proton

Identified?
The same resonance?



$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				
$X(3823)$				

Fig. 2. (Color online) Five groups of the charmonium-like states corresponding to five production mechanisms.

Hua-Xing Chen, Wei Chen, Xiang Liu, Shi-Lin Zhu, Phys. Rept. 639, 1(2016)

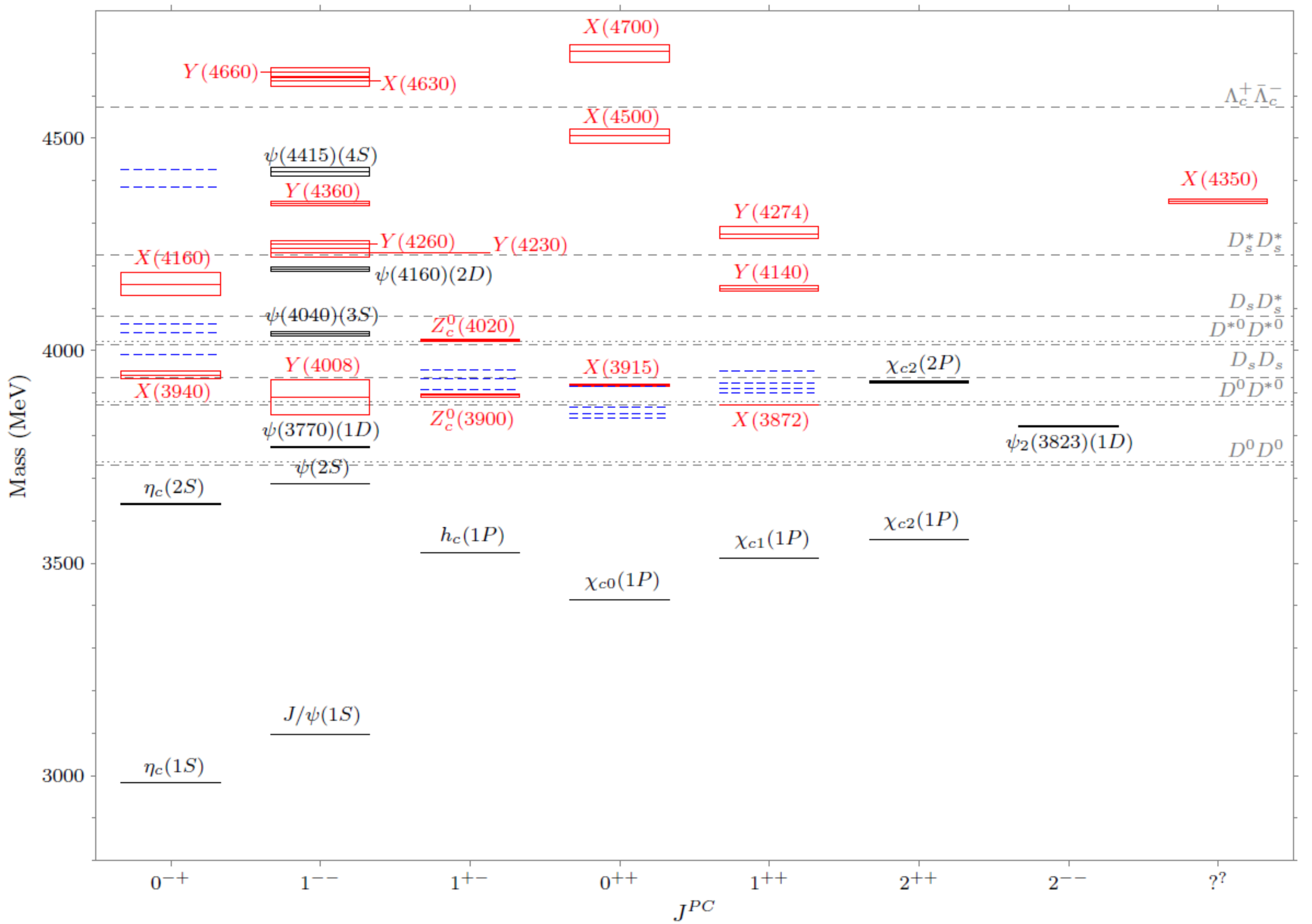


Figure 1: Level diagram for the neutral $c\bar{c}$ sector. Conventional, observed $c\bar{c}$ states are solid (black) lines labeled by Greek letters, the lowest predicted yet-unobserved conventional $c\bar{c}$ states are labeled with dashed (blue) lines (the clusters indicating predictions of several variant model calculations), and the solid (red) lines labeled by X, Y, or Z indicate exotic charmoniumlike candidates. Each measured state mass, including its central value and uncertainty, is presented as a rectangle (lines simply indicating very thin rectangles). Relevant thresholds are given by gray dashed lines; if a gray dotted line is nearby, it indicates the threshold isospin partner to the labeled dashed line. In some cases, likely quantum numbers have been assigned to states for which some uncertainty remains; this is the case, for example, for the $X(3940)$ and $X(4160)$, which have been studied as $\eta_c(3S)$, $\eta_c(4S)$ candidates. The actual known quantum numbers are listed in Table 2.

R.F. Lebed, Ryan E. Mitchell, Eric S. Swanson, arXiv:1610.04528

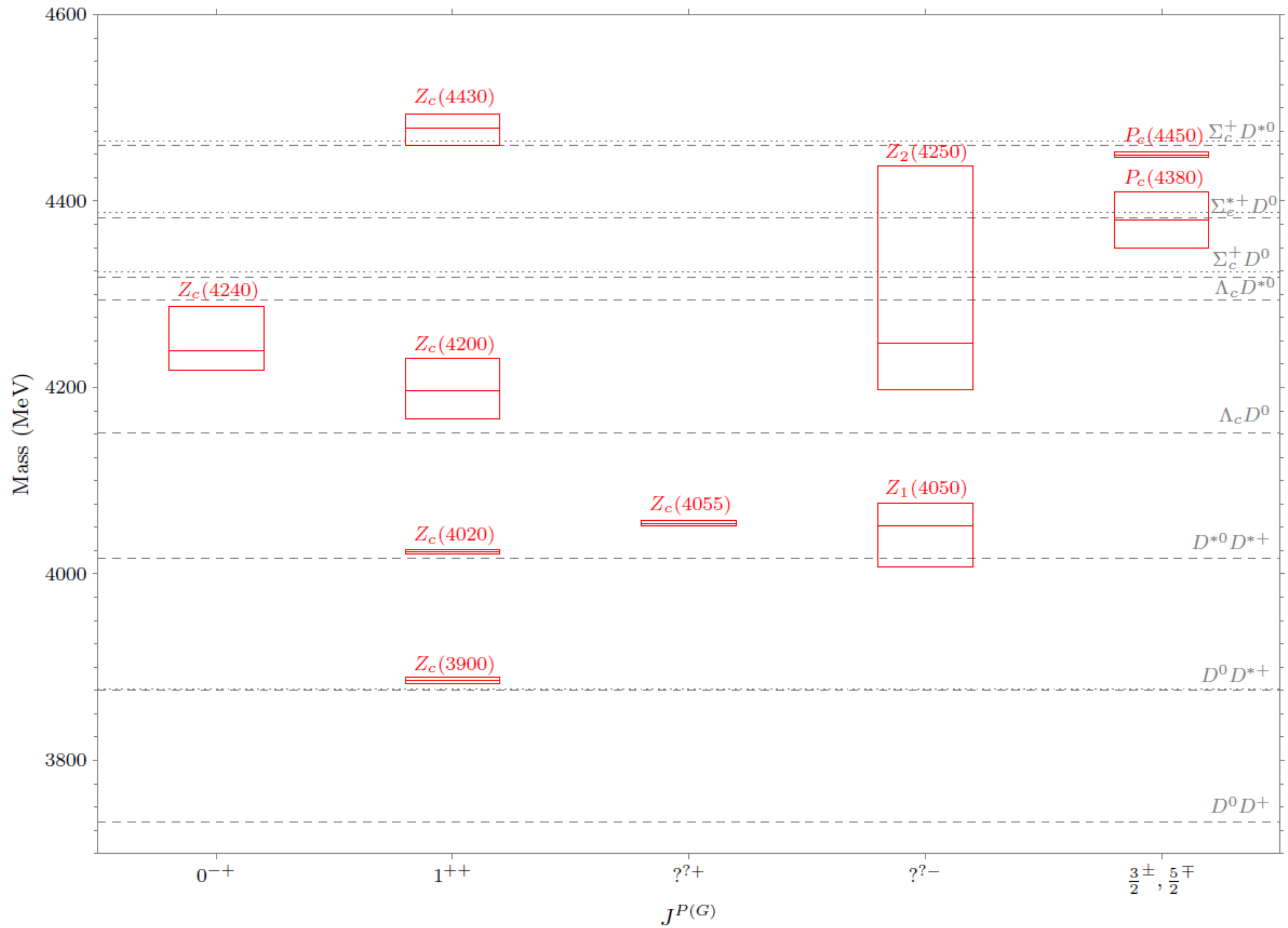


Figure 2: Charged charmoniumlike states, both bosonic and fermionic. Each measured state mass, including its central value and uncertainty, is presented as a rectangle. Relevant thresholds are given by gray dashed lines; if a gray dotted line is nearby, it indicates the threshold isospin partner to the labeled dashed line.

R.F. Lebed, Ryan E. Mitchell, Eric S. Swanson, arXiv:1610.04528

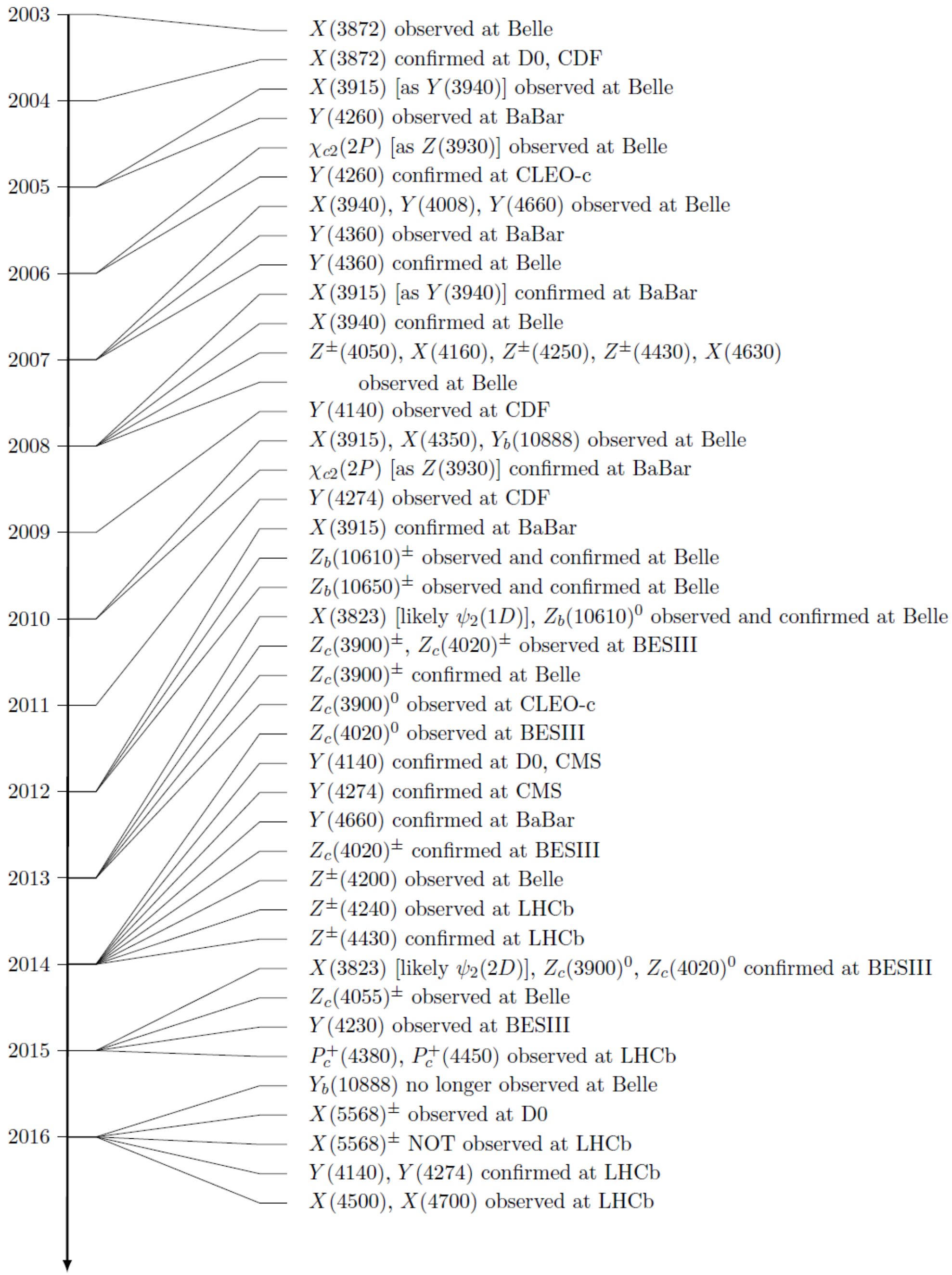


Figure 7: Timeline of discoveries of heavy-quark exotic candidates.

Table 1: Exotica organized by the way they are produced. References are given in the decay column.

Process	Production	Decay	Particle
B and Λ_b Decays	$B \to K + X$	$X \to \pi^+\pi^- J/\psi$ [4, 104, 105, 106, 107, 108, 109] $X \to D^{*0}\bar{D}^0$ [110, 111, 112] $X \to \gamma J/\psi$ [113, 114, 115, 116] $X \to \gamma\psi(2S)$ [113, 115]	$X(3872)$
		$X \to \omega J/\psi$ [101, 117, 118]	$X(3872)$ $Y(3940)$
		$X \to \gamma\chi_{c1}$ [119]	$X(3823)$
		$X \to \phi J/\psi$ [120, 121, 122, 123, 124, 125, 126, 127]	$Y(4140)$ $Y(4274)$ $X(4500)$ $X(4700)$
	$B \to K + Z$	$Z \to \pi^\pm\chi_{c1}$ [128, 129]	$Z_1(4050)$ $Z_2(4250)$
		$Z \to \pi^\pm J/\psi$ [43, 130]	$Z_c(4200)$ $Z_c(4430)$
		$Z \to \pi^\pm\psi(2S)$ [29, 130, 131, 132, 133, 134]	$Z_c(4240)$ $Z_c(4430)$
	$B \to K\pi + X$	$X \to \pi^+\pi^- J/\psi$ [135]	$X(3872)$
	$\Lambda_b \to K + P_c$	$P_c \to pJ/\psi$ [34]	$P_c(4380)$ $P_c(4450)$
e^+e^- Annihilation	$e^+e^- \to Y$	$Y \to \pi\pi J/\psi$ [22, 28, 136, 137, 138, 139]	$Y(4008)$ $Y(4260)$
		$Y \to \pi\pi\psi(2S)$ [103, 140, 141, 142]	$Y(4360)$ $Y(4660)$
		$Y \to \omega\chi_{c0}$ [143]	$Y(4230)$
		$Y \to \Lambda_c\bar{\Lambda}_c$ [144]	$X(4630)$
		$Y \to \pi\pi\Upsilon(1S, 2S, 3S)$ [145, 146] $Y \to \pi\pi h_b(1P, 2P)$ [147]	$Y_b(10888)$
	$e^+e^- \to \pi + Z$	$Z \to \pi J/\psi$ [21, 22, 30, 31] $Z \to D^*\bar{D}$ [32, 148, 149]	$Z_c(3900)$
		$Z \to \pi h_c$ [150, 151] $Z \to D^*\bar{D}^*$ [152, 153]	$Z_c(4020)$
		$Z \to \pi^\pm\psi(2S)$ [142]	$Z_c(4055)$
		$Z \to \pi\Upsilon(1S, 2S, 3S)$ [154, 155, 156] $Z \to \pi h_b(1P, 2P)$ [154]	$Z_b(10610)$ $Z_b(10650)$
		$Z \to B\bar{B}^*$ [157]	$Z_b(10610)$
		$Z \to B^*\bar{B}^*$ [157]	$Z_b(10650)$
	$e^+e^- \to \gamma + X$	$X \to \pi^+\pi^- J/\psi$ [49]	$X(3872)$
	$e^+e^- \to \pi^+\pi^- + X$	$X \to \gamma\chi_{c1}$ [158]	$X(3823)$
	$e^+e^- \to J/\psi + X$	$X \to D\bar{D}^*$ [38, 159]	$X(3940)$
		$X \to D^*\bar{D}^*$ [38]	$X(4160)$
$\gamma\gamma$ Collisions	$\gamma\gamma \to X$	$X \to \omega J/\psi$ [160, 161]	$X(3915)$
		$X \to D\bar{D}$ [162, 163]	$Z(3930)$
		$X \to \phi J/\psi$ [164]	$X(4350)$
Hadron Collisions	pp or $p\bar{p} \to X+$ anything	$X \to \pi^+\pi^- J/\psi$ [26, 165, 166, 167]	$X(3872)$
		$X \to \phi J/\psi$ [168]	$Y(4140)$
		$X \to B_s\pi^\pm$ [169]	$X(5568)$

Do multiquark hadrons exist?

VOLUME 48, NUMBER 10 PHYSICAL REVIEW LETTERS 8 MARCH 1982

Do Multiquark Hadrons Exist?

John Weinstein and Nathan Isgur
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(Received 30 November 1981)

The $qq\bar{q}\bar{q}$ system has been examined by solving the four-particle Schrödinger equation variationally. The main findings are that (1) $qq\bar{q}\bar{q}$ bound states normally do not exist, (2) the cryptoexotic 0^{++} sector of this system with $K\bar{K}$ quantum numbers is probably the only exception to (1) and its bound states can be identified with the S^* and δ just below $K\bar{K}$ threshold, (3) $qq\bar{q}\bar{q}$ bound states provide a model for the weak binding and color-singlet clustering observed in nuclei, and (4) there is no indication that this system has strong resonances.

Four-quark states in lattice

Hadronic molecules in lattice QCD

Chris Stewart and Roman Koniuk
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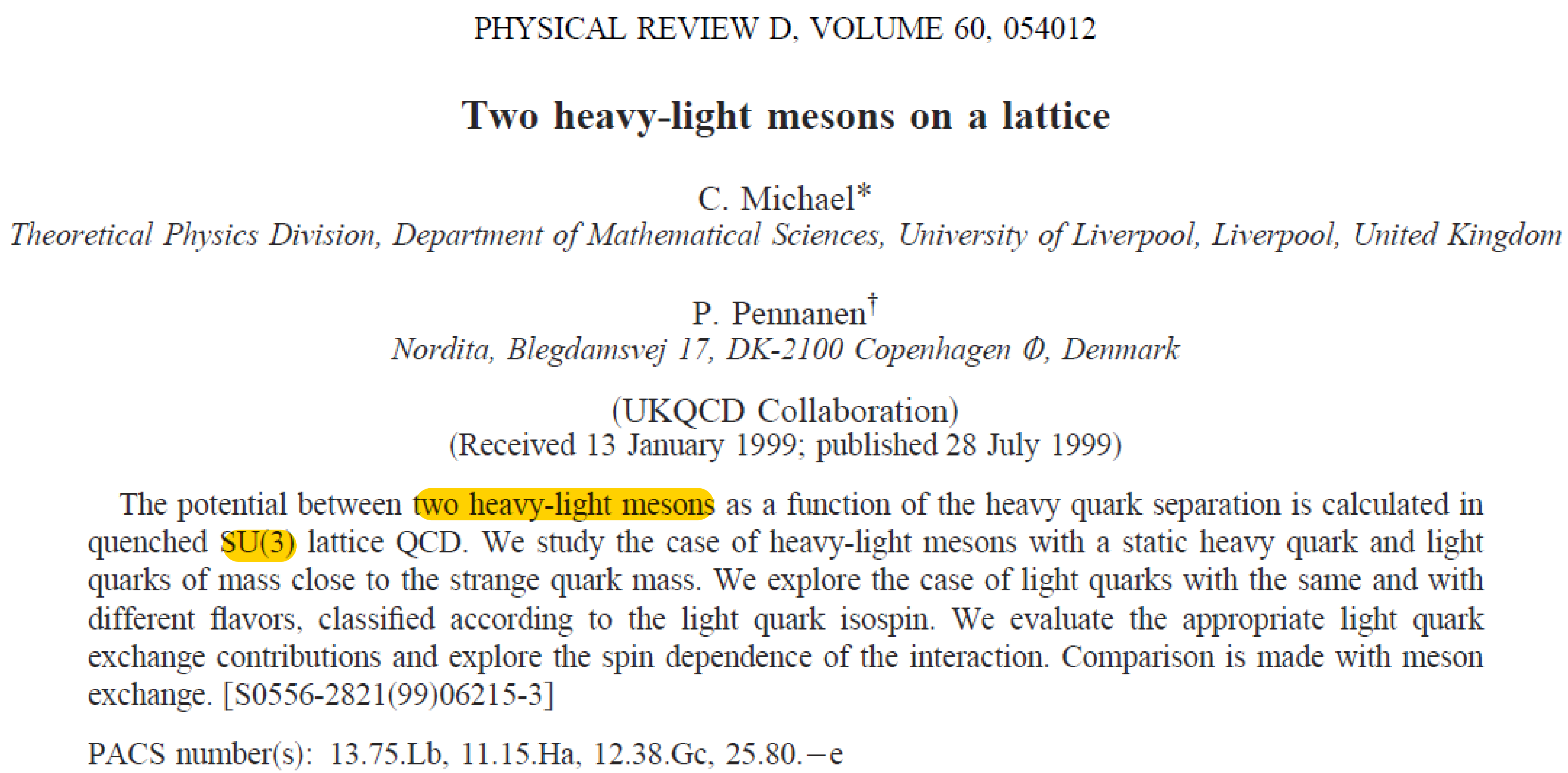
(Received 17 November 1997; published 7 April 1998)

An adiabatic approximation is used to derive the binding potential between two heavy-light mesons in quenched SU(2)-color lattice QCD. Analysis of the meson-meson system shows that the potential is attractive at short and medium range. The numerical data is consistent with the Yukawa model of pion exchange. [S0556-2821(98)02911-7]

PACS number(s): 12.38.Gc, 12.38.Aw, 24.85.+p

Four-quark states in lattice



PHYSICAL REVIEW D, VOLUME 60, 054012

Two heavy-light mesons on a lattice

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P. Pennanen†

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(UKQCD Collaboration)

(Received 13 January 1999; published 28 July 1999)

The potential between two heavy-light mesons as a function of the heavy quark separation is calculated in quenched SU(3) lattice QCD. We study the case of heavy-light mesons with a static heavy quark and light quarks of mass close to the strange quark mass. We explore the case of light quarks with the same and with different flavors, classified according to the light quark isospin. We evaluate the appropriate light quark exchange contributions and explore the spin dependence of the interaction. Comparison is made with meson exchange. [S0556-2821(99)06215-3]

PACS number(s): 13.75.Lb, 11.15.Ha, 12.38.Gc, 25.80.−e

Systems with heavy quarks should be more easily bound provided the potential is attractive, since the repulsive kinetic energy of the quarks is smaller, while the attractive two-body potential remains the same.

Four-quark states from lattice

PHYSICAL REVIEW D **87,** 114511 (2013)

Lattice QCD signal for a bottom-bottom tetraquark

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Marc Wagner†

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(European Twisted Mass Collaboration)

(Received 29 September 2012; revised manuscript received 6 June 2013; published 20 June 2013)

Utilizing lattice QCD results for the potential of two static antiquarks and two dynamical quarks as well as quark model techniques for the dynamics of two heavy antiquarks in a cloud of two light quarks, we are provided with an accurate framework for the study of possibly existing heavy-heavy-light-light tetraquarks. Among the possible quantum numbers of such a system, we find binding in only one channel the scalar isosinglet. Solving the Schrödinger equation for the displacement of the heavy antiquarks and taking systematic errors into account, we find an antibottom-antibottom-light-light bound state with a confidence level of around 1.8σ–3.0σ and binding energy of approximately 30–57 MeV.

Tetraquark

Four-quark states from lattice

PHYSICAL REVIEW D **92,** 014507 (2015)

Evidence for the existence of $ud\bar{b}\bar{b}$ and the nonexistence of $ss\bar{b}\bar{b}$ and $cc\bar{b}\bar{b}$ tetraquarks from lattice QCD

Pedro Bicudo,[1] Krzysztof Cichy,[2,3] Antje Peters,[2] Björn Wagenbach,[2] and Marc Wagner[2]
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[2]*Johann Wolfgang Goethe-Universität Frankfurt am Main, Institut für Theoretische Physik, Max-von-Laue-Straße 1, D-60438 Frankfurt am Main, Germany*
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(Received 13 May 2015; published 29 July 2015)

We combine lattice QCD results for the potential of two static antiquarks in the presence of two quarks qq of finite mass and quark model techniques to study possible existing $qq\bar{b}\bar{b}$ tetraquarks within the Born-Oppenheimer approximation. While there is strong indication for a bound four-quark state for $qq = (ud - du)/\sqrt{2}$, i.e., isospin $I = 0$, which is stable with respect to QCD, i.e., can only decay weakly, we find clear evidence against the existence of corresponding tetraquarks with $qq \in \{uu, (ud + du)/\sqrt{2}, dd\}$, i.e., isospin $I = 1$, $qq = ss$, and $qq = cc$.

Tetraquark

Four-quark states from lattice

arXiv: 1608.06537

Hadro-quarkonium from Lattice QCD

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The hadro-quarkonium picture [1] provides one possible interpretation for the pentaquark candidates with hidden charm, recently reported by the LHCb Collaboration, as well as for some of the charmonium-like "X, Y, Z" states. In this model, a heavy quarkonium core resides within a light hadron giving rise to four- and five-quark/antiquark bound states. We test this scenario in the heavy quark limit by investigating the modification of the potential between a static quark-antiquark pair induced by the presence of a hadron. Our lattice QCD simulations are performed on a CLS ensemble with $N_f = 2+1$ flavours of non-perturbatively improved Wilson quarks at a pion mass of about 223 MeV and a lattice spacing of about $a = 0.0854$ fm. We study the static potential in the presence of a variety of light mesons as well as of octet and decuplet baryons. In all these cases, the resulting configurations are favoured energetically, however, the associated binding energies between the quarkonium in the heavy quark limit and the light hadron are found to be smaller than a few MeV, similar in strength to deuterium binding.

Hadro-quarkonium

2. Hunting for diquark

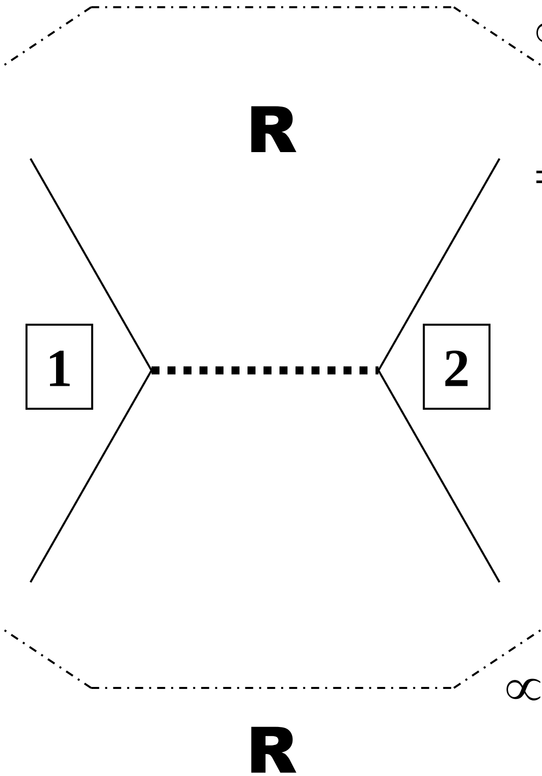
Quarks/antiquarks in hadron containing more than 3 quarks may have complicated correlations and form different clusters

Gell-Mann (1964) first mentioned the possibility of diquarks in his original paper on quarks. Later, Ida and Kobayashi (1966) and Lichtenberg and Tassie (1967) introduced diquarks in order to describe a baryon as a composite state of two particles, a quark and diquark.

M. Gell-Mann, Phys. Lett. 8, 214 (1964);
M. Ida and R. Kobayashi, Prog.Theor.Phys. 36 (1966) 846;
D.B. Lichtenberg and L.J. Tassie, Phys.Rev. 155 (1967) 1601

Attractive & repulsive channels in QCD

Interaction of two colored objects:



$$\propto g^2 < \vec{T}_1 \cdot \vec{T}_2 >_R = \frac{g^2}{2}\left[< (\vec{T}_1 + \vec{T}_2)^2 >_R - < \vec{T}^2 >_1 - < \vec{T}^2 >_2 \right] =$$

$$= \frac{g^2}{2}\left[C^{(2)}(R) - C^{(2)}(1) - C^{(2)}(1) \right]$$

$\bar{q}q = \{$

	octet = +1/3	repulsion
	singlet = -8/3	attraction

$qq = \{$

	"3bar" = -4/3	attraction
	"6 " = +2/3	repulsion

Spin-spin interaction

$$\propto -g^2 < \sigma_1 \vec{T}_1 \cdot \sigma_2 \vec{T}_2 >_R \propto -g^2 \left[C^{(2)}{}_{eff}(R) \right]\left[J(J+1) - 3/2 \right]$$

$< \bar{q}q >_1 \ and < qq >_{\bar{3}} = \{$

	spin 1= +1/2	repulsion
	spin 0= -3/2	attraction

Baryons in the octet:

□Λ=([ud] $_{J=0}$ s); Σ^0 =({ud}$_{J=1}$s)$\rightarrow$ Λ is lighter than Σ

From L.MAIANI. Scalar Mesons & 4-quarks

According to the following references, the two quarks correlate antisymmetrically in color, flavor, and spin, separately, and thereby attract one another forming a "good" diquark cluster,

Good diquark

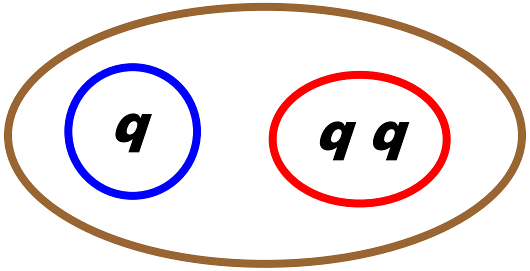
$$[qq]:\ |\bar{3}_c, \bar{1}_s, \bar{3}_f\rangle$$

Bad diquark

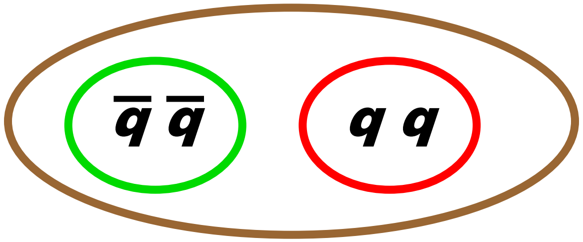
$$(qq):|\bar{3}_c, 3_s, 6_f\rangle$$

R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. 91, 232003 (2003);
R. L. Jaffe, Phys. Rep. 409, 1 (2005).
A. Selem and F. Wilczek, arXiv:hep-ph/0602128.

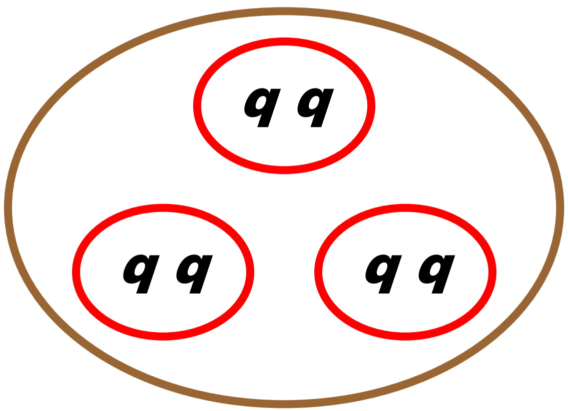
Possible bound states including diquarks



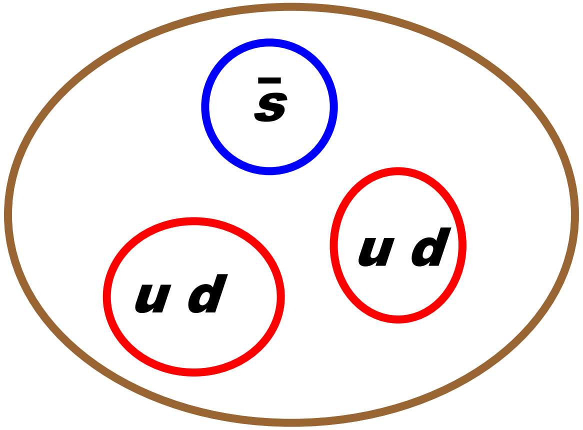
baryons ?



four-quark states?



dibaryons ?



pentaquark ?

Remember: possible quark and anti-quark combinations are of the form

$$(3q)^p (q\overline{q})^n \;\; (p, n \geq 0)$$

Diquark picture

Hunting for diquark in lattice

D.B. Leinweber, "Do quarks really form diquark clusters in the nucleon?", Phys. Rev. D47, 5096(1993)

PHYSICAL REVIEW D VOLUME 47, NUMBER 11 1 JUNE 1993

Do quarks really form diquark clusters in the nucleon?

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(Received 7 July 1992; revised manuscript received 12 January 1993)

A gauge-invariant method for the investigation of scalar diquark clustering in the nucleon ground state is presented. The method focuses on a comparison of quark distributions in the nucleon with those in the Δ baryon resonance. Recent lattice QCD calculations of these quark distribution radii are analyzed in a search for evidence of scalar diquark clustering. The analysis indicates the lattice results describe the negative squared charge radius of the neutron with little resort to hyperfine clustering between u-d quark pairs. This result contrasts both quark-diquark and nonrelativistic quark models where hyperfine attraction between u and d quarks in the nucleon is argued to play a significant role. Comparison of light quark distributions in Λ^0 and Σ^{*0} indicate only a small reduction of the scalar diquark distribution radius relative to the vector diquark distribution. Current lattice QCD determinations of baryon charge distributions do not support the concept of substantial u-d scalar diquark clustering as an appropriate description of the internal structure of the nucleon.

PACS number(s): 13.40.Fn, 12.38.Gc, 14.20.Dh

PHYSICAL REVIEW D, VOLUME 58, 111502

Diquark masses from lattice QCD

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(Received 8 May 1998; published 28 October 1998)

We present the first results for diquark correlation functions calculated in the Landau gauge on the lattice. Masses have been extracted from the long distance behavior of these correlation functions. We find that the ordering of the diquark masses with spin 0 and 1 states in color anti-triplet and sextet channels is in accordance with instanton motivated interaction models. Although we find evidence for an attractive interaction in color anti-triplet states with a splitting between spin 0 and spin 1 diquarks that can account for the mass splitting between the nucleon and the delta, there is no evidence for a deeply bound diquark state.

Evidence for Diquarks in Lattice QCD

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(Received 5 September 2006; published 30 November 2006)

Diquarks may play an important role in hadron spectroscopy, baryon decays, and color superconductivity. We investigate the existence of diquark correlations in lattice QCD by considering systematically all the lowest energy diquark channels in a color gauge-invariant setup. We measure mass differences between the various channels and show that the positive parity scalar diquark is the lightest. Quark-quark correlations inside the diquark are clearly seen in this channel, and yield a diquark size of $\mathcal{O}(1)$ fm.

PHYSICAL REVIEW D **77,** 034505 (2008)

Diquark effects in light baryon correlators from lattice QCD

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We study the role of diquarks in light baryons through point-to-point baryon correlators. We contrast results from quenched simulations with ones with two flavors of dynamical overlap fermions. The scalar, pseudoscalar, and axial vector diquarks are combined with light quarks to form color singlets. The quenched simulation shows large zero-mode effects in correlators containing the scalar and pseudoscalar diquark. The two scalar diquarks created by γ_5 and $\gamma_0\gamma_5$ lead to different behavior in baryon correlators, showing that the interaction of diquarks with the third light quark matters: we do not see an isolated diquark. In our quark mass range, the scalar diquark created by γ_5 seems to play a greater role than the others.

Hunting for diquark in mass spectrum

Model dependence!

Hunting for diquark in hadron decays

Important in both theory and experiment!

Diquark signal in experiment?

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Experimental signal for diquarks in quark-gluon plasma

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We will discuss how a substantial presence of diquarks (correlated pairs of light quarks) can alter the ratio of Λ_c/Σ_c in heavy-ion collisions. This can be used as a signal for the presence of diquarks in the plasma and also as an indication for the existence of deconfined matter.

Hadronic decays in highly excited Λ_Q and Ξ_Q baryons?

3. Hunting for multiplets

Scalar

Nonet of scalar and color singlet states:

$[ud][\bar{u}\bar{d}]$ transforms as $\bar{s}s$ $(I = 0)$

$[ud][\bar{d}\bar{s}]$ transforms as $\bar{s}u$ $(I = 1/2)$

$[us][\bar{d}\bar{s}]$ transforms as $\bar{d}u$ $(I = 1)$

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys.Rev.Lett, 93,212002(2004)

$$a^0(I=1, I_3=0) = \frac{1}{\sqrt{2}}([su][\bar{s}\,\bar{u}] - [sd][\bar{s}\,\bar{d}]),$$

$$f_0(I=0) = \frac{1}{\sqrt{2}}([su][\bar{s}\,\bar{u}] + [sd][\bar{s}\,\bar{d}]),$$

$$\sigma_0(I=0) = [ud][\bar{u}\,\bar{d}], \qquad \kappa = [ud][\bar{s}\,\bar{d}],$$

Maiani (2012)

X, Y, Z

Experiment: Belle, BaBar, BES, Cleo ....

Possible interpreations: tetraquarks

$$Z(4430) \to J/\psi \ \ \pi^+ : \ [cu]^{S=0}[\bar{c}\bar{d}]^{S=1} + [cu]^{S=1}[\bar{c}\bar{d}]^{S=0}, \quad 2S$$

$$Y(4260) \quad : \ [cs]^{S=0}[\bar{c}\bar{s}]^{S=0} \quad P$$

$$X(3872) \quad : \ [cd]^{S=0}[\bar{c}\bar{d}]^{S=1} + [cd]^{S=1}[\bar{c}\bar{d}]^{S=0} \quad 1S$$

$$X(3876) \quad : \ [cu]^{S=0}[\bar{c}\bar{u}]^{S=1} + [cu]^{S=1}[\bar{c}\bar{u}]^{S=0} \quad 1S$$

L.Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys.Rev. D89, 11(2014) , 114010; Phys.Rev.Lett. 99, 182003(2007) ; Phys.Rev. D72 (2005) 031502; Phys.Rev. D71, 014028(2005) ;

Phys. Rev. D94, 054026(2016)

q → s ?

Summary Table

radial	particle	J^{PC}	input	predicted	notes
$1S$	X_0	0^{++}		4040	below the $J/\Psi\ \phi$ threshold
$1S$	X	1^{++}	4140		$--$
$1S$	$X^{(1)}$	1^{+-}		4140	decays in $\chi_c\phi$? $(M \geq 4435)$
$1S$	$X^{(2)}$	1^{+-}		4240	decays in $\eta_c\phi$?
$1S$	X_0'	0^{++}		4240	part of 4274 structure?
$1S$	X_2'	2^{++}		4240	part of 4274 structure?
$2S$	X_0	0^{++}	4500		$--$
$2S$	X	1^{++}		4600	$--$
$2S$	$X^{(1)}$	1^{+-}		4600	$S_{c\bar{c}} = 1$ decays in $\chi_c\phi$?
$2S$	$X^{(2)}$	1^{+-}		4700	$S_{c\bar{c}} = 0$ decays in $\eta_c(2S)\phi$?
$2S$	X_0'	0^{++}	4700		$--$
$2S$	X_2'	2^{++}		4700	decays in $J/\Psi\phi$, $\psi'\phi$?

Table 1: Input and predicted masses for $1S$ and $2S$ cs tetraquarks.

c → b ?

Alternative explanations of the data that are based on less exotic quark-based interactions exist?

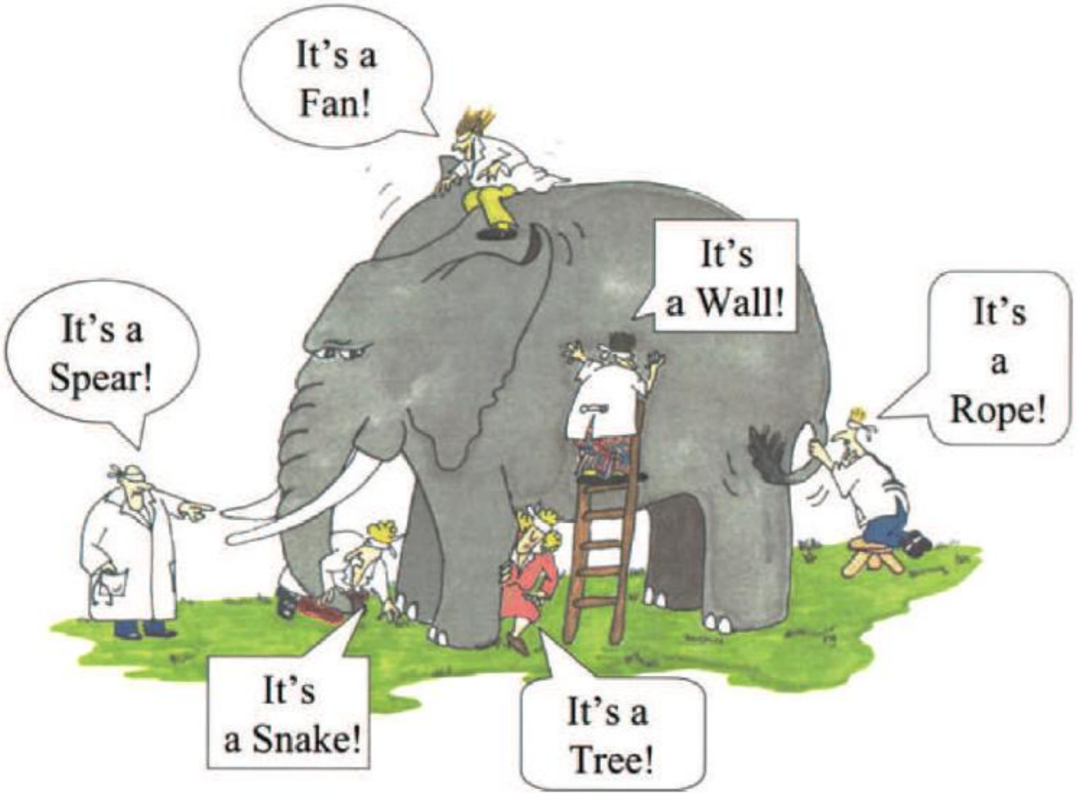
Kinematics effect?

Final state interactions?

Threshold effect?

…

Study of exotics



Our work on four-quark state and diquark

Ailin Zhang, "Four quark state in QCD", Phys. Rev. D61, 114021 (2000)

Ailin Zhang, Tao Huang and Tom. Steele, "Diquark and light four-quark states", Phys. Rev. D76, 036004 (2007)

Bing Chen, Deng-Xia Wang and Ailin Zhang, "J^P Assignments of Λ_c^+ Baryons", Chin.Phys.C33,1327(2009)

R. T. Kleiv, T. G. Steele, Ailin Zhang and Ian Blokland, "Heavy-light diquark masses from QCD sum rules and constituent diquark models of tetraquarks" , Phys.Rev. D87, 125018 (2013)

Bing Chen, Ke-Wei Wei and Ailin Zhang, "Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture", Eur.Phys.J. A51, 82(2015)

4. Discussion without conclusion

- Has four-quark state been found?
- Where is the diquark signal?
- Where is the multiplet?
- More study in theory and experiment!

Thanks!